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# TRENDS IN SENSORS FOR SPATIALLY VARIABLE CONTROL OF FIELD MACHINERY

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Abstract. Not all spatially variable properties of soil and plants are really essential for the in-field site-specific plant production. Only those quantities with high variability and great influence on economic returns should be considered seriously, like the availability of the nutrients or the population of weed and pest. Practicable solutions for on-line sensing of nutrients and state of plants or soil have not been introduced yet, proposals are under discussion. To monitor the state of the soil regarding tillage or fertilizing, in general, one has to evaluate a set of composite quantities. It seems that sensing for organic matter content by optical methods or for nitrate by ion-selective electrodes might be sufficient for a first order evaluation and can be introduced into the practice in future. Measurements like tractive power or pressure in horizontally moved penetrometers are applicable for on-the-go monitoring of dynamic soil properties. Machine vision may be used for the evaluation of the quality of tillage and plants. The application of biocides depends on the state of plants, which means imaging of shape and colour, a question principally solved, but really cost-effective systems are not available yet.

Keywords: sensor, field machinery

## SITE-SPECIFIC AGRICULTURE-INFORMATION: VARIABILITY AND CHANGEABILITY

The conventional methodology of farming aims at homogeneous control and uniform treatment of fields as basic units. Tillage, soil measurements, fertilizing, sawing, plant protection, etc. follow standard procedures and may be changed and adopted by farmer's eye and experience. The advances in knowledge, electronics and machine design give way for precision (or spatially variable or site-specific) crop production. Several studies on grain yields or on nitrate and other nutrient levels have shown high variability and changeability within one field [e.g., 5,10,19,22]. Site-specific cropping will not equalise yield but optimise economic returns taking into consideration the actual stage of the soil in relation to the local need of the specific crop. The necessary action like tillage, fertilizing or spraying chemicals may be controlled by the evaluation of plant growing and managerial modelling. This means sensing of soil and plant, but also management, control, positioning, and of course, adopting all other conditions, the farmer is facing traditionally. A benefit of the new technology is the increase of the use efficiency of energy and chemicals, such a way more environment friendly agriculture will be introduced.

The growth of plants depends on soil and climatic conditions. Site-specific production should provide plants an appropriate nutrient and protection level. Therefore, soil, water, and plants must be controlled. In soil we find spatial variations of structure (density, porosity, etc.) and composition (organic matter, minerals, water, ions, etc.), which may change due to temperature, rainfall, biological and human activity, etc. Structural and compositional variations can have a typical length (correlation length) in dependence on property from molecular distances up to continental dimensions. Because of dynamic character of agricultural work (speed 1-2 m/s) and since sensing and acting has a limited time resolution of>0.1 s, usually of about 1 s, only variations with a correlation length between one meter and the length of the field will be considered for site-specific crop production.

Soil fertility is determined by biological, chemical and physical quantities. The farmer can influence some of these properties directly. The weed potential and the soil structure profile (density, porosity, and soil aggregate distribution mainly) are the source for information on necessary intensity of tillage. Although there is traditional experience concerning tillage related to soil conditions and crop, the soil structure is anisotropic with different correlation lengths, therefore, site-controlled tillage depth may improve local fertility or save energy due to reduction of tillage depth. The more important field for economic returns in site-specific crop production is the application of chemicals (fertilizer, plant protection), since influence on the yield due to the local variability and changeability is considerably higher.

In general, site-specific crop production belongs to a new type of agriculture, which may be called Information Controlled Agriculture and sensors are needed for two different purposes: (i) to get information on objects to be handled (soil, plant), and (ii) to control the action of the machine (position of tools, working depth, grain volume or mass, etc.). In this paper the trend in sensors for (iii) will be considered only. Table 1 gives a survey on variability and information in relation to cropping processes with a qualitative rank order for the demand of sensors.

## TRENDS IN SOIL SENSING

Information on the state of the soil may be got as on-the-go monitoring of variable quantities in line with immediate responds of the machine system. The other possibility is the decoupling in time of sensing and control action. This is possible for quantities which will not change essentially meanwhile or where the change can be calculated accurately. This type of temporally separate control in agriculture requires positioning and field mapping. Sensors are needed in each case, since all actions must be based on necessary information.

Soil as composed system has complex interrelated properties. The fertility of soil depends on its structure and chemical components. The easiest way of influencing the fertility is adding of nutrients as fertilizers and manure. Therefore, the determination of the real need by soil sensing for nutrients seems to be the most important step in site-specific agriculture. The moisture profile of the soil, which cannot be controlled except on irrigated fields, should be known too, since solution and distribution of chemicals applied as well as mechanical properties of the soil are depending on moisture content and moisture distribution.

### Principles and trends of nutrient sensing technology

There are several ways for nutrient sensing (Fig. 1). The best possibility would be a complete concentration analysis of the plant available nutrient ions in the soil water. Since the ion concentration of the soil water is connected with soil structure and type of soil minerals, sensing of minerals could be a source for information on nutrient content. Unfortunately, the most important nutrient nitrogen is supplied by organic sources only and the concentration of the other nutrients does not depend on the soil minerals directly, since several factors like pH or humic acids are involved.

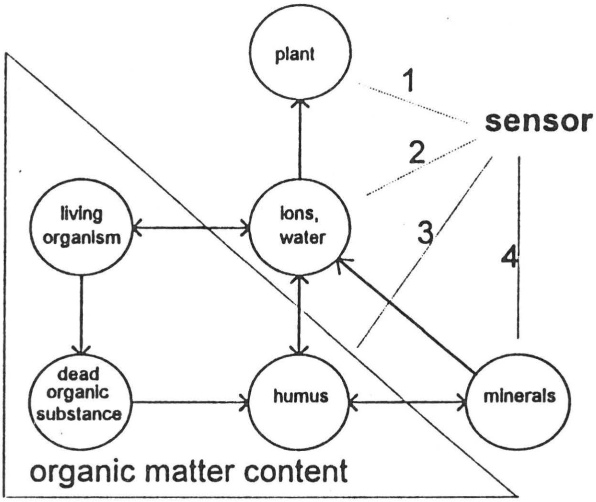
The chemical composition of plants is partially influenced by the nutrient content of the soil. Therefore, the analysis of plants might be used for getting of information on the nutrient content of the soil as well. Variations in the elemental composition of plants indicate shortages in the availability of nutrients. In terms of quantity and cost, the important fertilizers in practice are nitrogen, potassium, and phosphorus. Magnesium and calcium (usually as lime) are widely applied too, because they are nutrients

**Table 1.** Site-specific crop production - variability, information and examples for sensor need (soil and crop control; *for various processes)

| Process | Type of variability (dependence) | Information needed for actual manipulation | Information gained by sensing during processing | Sensor demand for site-specific quantity 1 (high) ... 3 (low) | |
|---|---|---|---|---|---|
| Tillage | - task (aim; past)<br>- time (weather, season)<br>- space (horizontally low and vertically high variability in soil condition) | - soil conditon (type, mechanical properties, porosity, moisture, ...) | -locall variations in mechanical properties (electronic soil mapping);<br>-change in soil conditions | ploughing depth<br>surface structure*<br>soil moisture* | 3<br>2<br>2 |
| Sowing and planting | -task (aim; past)<br>-time (weather, season)<br>-space (task and soil conditon) | -position<br>-drilling intensity/ placing distances (area density, row distance)<br>-sowing/planting depth | -area density and distribution of plants | | |
| Manure and fertilizer | -task (aim; past)<br>-time (weather, season)<br>-space (local variation of organic matter and minerals) | -need by plant<br>-local concerning and distribution of organic matter and minerals (free and fixed) | -change in local concentration and distribution of organic matter and minerals | nutrient content<br>organic matter content* | 1<br>1 |
| Plant protection | -task (aim; state of plants)<br>-time (weather, stage of plant development)<br>-space (local variation of plants, weeds and pest) | -position<br>-weather condition<br>-local distribution of the state of plants and of the weed or pest population | -type and area density of chemicals applied<br>-local potential for weed and pest | state of plants*<br>weed & pest (type, density) | 3<br>1 |
| Harvest | -task (aim)<br>-time (weather)<br>-space (area density and distribution of plants) | -stage of rileness<br>-moisture conent | -type of crop and yield per area (local distribution)<br>-extractiion of minerals<br>-production of soil organic matter | | |

and support the soil fertility especially due to pH regulation. Nitrogen is not contained in minerals and its concentration in the soil depends on biological activity and on organic matter content. Therefore, the determination of organic matter content in the soil is a useful way in nutrient sensing.

Sensors for the measurement of ion concentration are commercially available already. Two principles are used, (i) pure diffusion controlled measurement (ion-selective electrodes and solid-state electro-chemical sensors), and (ii) chemical reaction controlled measurement (chemical reaction with colour evaluation or chemical surface reaction with change of measurable physical quantity like refraction index, charge at the gate of an FET, etc.). Usually, the measurement of ions is a time and money consuming process and requires contact sensing, a procedure difficult to realise in agricultural practice. But Adsett and Zoerb [1] have designed a prototype of a soil sampling and extracting equipment for automatic field monitoring of soil nitrate levels using a flow cell with a built-in nitrate-selective electrode (Fig. 2). Their results show that this technology gives acceptable accuracy, reproducibility



plant: $\sum_i a_i Nu_i$ and $a_i = F(b_i)$

ions: $\sum_i b_i Nu_i$ and $b_i = F(a_i, c_i, d_i)$

organic matter: $\sum_i c_i Nu_i$ and $c_i = F(a_i, b_i, d_i)$

minerals: $\sum_i d_i Nu_i$

$Nu_i$ : C, H, O, N, P, K, Ca, Mg, S, B, Cu, Mn, Mo, Zn, Cl, Na

**Fig. 1.** Principal possibilities for soil nutrient sensing.

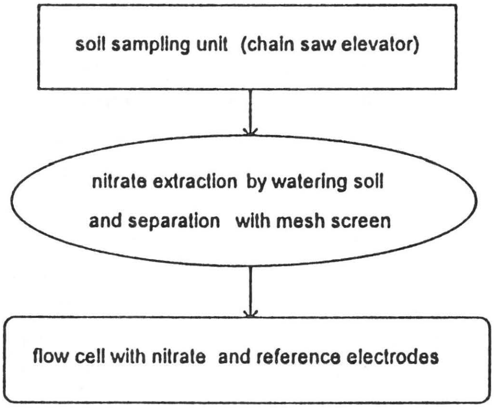


**Fig. 2.** Scheme for automatic a field monitoring of soil nitrate levels [1].

and response times (in the order of few seconds). Difficulties occurred in the operation of the extraction unit and the calibration process. Although they recommend the use of this type of equipment by specialized contractors only, one clear way for soil nutrient on-the-go sensing has been presented and could accelerate further research and development in this field.

True sensors for elementary analysis of plants and minerals are not known. Multielemental analysis methods are based upon spectral measurements of emission, absorption or fluorescence of excited atoms. The excitation may be produced by heating or by electromagnetic energy. Laboratory methods like Atomic Absorption Spectroscopy

(AAS), Atomic Emission Spectroscopy (AES), or X-ray Fluorescence Analysis (XFS or AFS) are well known. The best potential for a sensor design has the old-fashioned spark spectrometry, which uses the characteristic spectral lines of atoms emitted from plasma discharge at atmospheric pressure. Higher accuracy and sensitivity are possible, when for the plasma generation a pulsed high power laser is used [8]. Since the laser applications are getting cheaper more and more, a sensor based on laser plasma emission (LPE) or on laser plasma absorption (LPA) may be the way for the on-the-go analysis of plants and soil in future (Fig. 3).

The organic matter content can be measured by thermal and chemical methods (combustion of dry soil and change in mass or $CO_2$-gravimetry). The best scientific method might be the C13-Magnetic Resonance, since one will get the concentrations of the components of the soil organic matter [12]. These methods are not suitable for sensor development. There are two other principles: (i) Measurement of the $CO_2$-concentration of the soil air, because the $CO_2$-content correlates with biological activity, which itself depends on organic matter too. Sensors would be contact based, which of course limits the use of this type of sensors. (ii) The colour and NIR-absorbance (or reflectance) of the soil are influenced by the organic matter content. Therefore, optical methods have been used for the development of sensors for organic matter content determination [e.g., 14,28,33,34].

The difficulty in applying optical methods for soil sensing is caused by partial interrelation of soil properties influencing

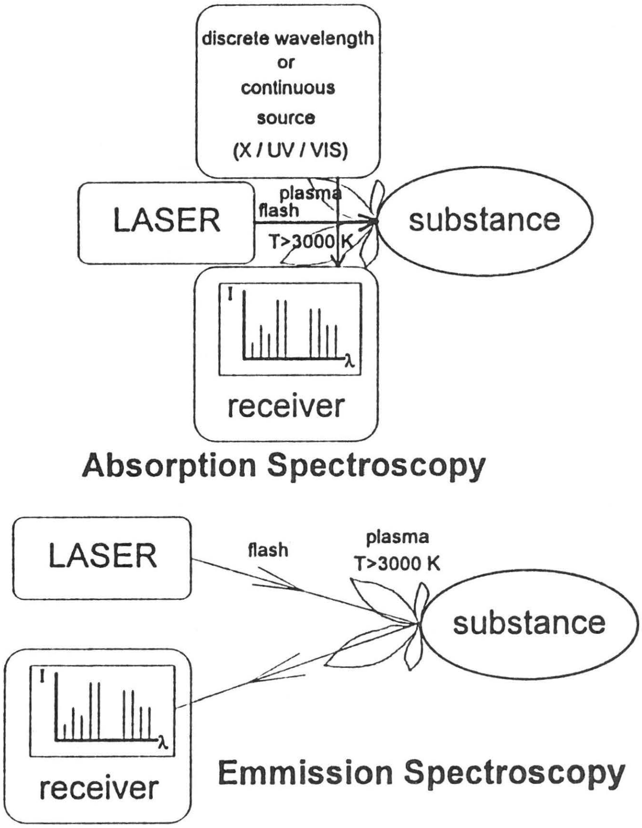


**Fig. 3.** Principle of Pulsed Laser Plasma Absorption and Emission Spectroscopy.

the reflectance like soil texture, surface roughness, composition of minerals, content of moisture or organic matter. To overcome this situation, the best way would be the sensing of all properties by independent sensors. Additionally, reflection gives information about the reflecting surface with a depth of few microns only. Since the concentration profile of the organic matter content up to a depth of around 30 cm is of interest, the distribution function must be known or an equipment for three-dimensional on-the-go soil sample collecting must be used. The practical tests [14,28,33] have shown that a calibration according to the different type of soils to be controlled gives sufficient accuracy in soil sensing. Shonk *et al.* [28] used a one-line sensor (LED at 660 nm) whereas Sudduth *et al.* [34] found the best approximation by evaluation of 12 points (multispectral filter with a bandwidth of 55 nm) between 1700 and 2420 nm. In this spectral range we find excitation of electron and lattice vibrations leading to typical continuous solid state absorption. Groups of atoms like the radicals CH, NH, HO, or HS, which are components of organic matter, produce harmonic vibrations between 800 nm and 2500 nm, thus broad absorption bands of nearly all organic compounds are measurable in the NIR range.

### Principles and trends of soil moisture sensing

The field methods for fast soil moisture determination may be subdivided into contact and non-contact methods. There are many principles and studies concerning moisture determination. Reviews to this field have been given several times [e.g., 23,27,30]. The measurement of conductivity, dielectricity or heat conductivity is carried out by contact methods usually. The measurement of resistance or current (conductivity) gives principally incorrect results, since the concentration and mobility of ions and not the concentration of water molecules is measured. The change in capacitance is not determined by the moisture content alone but depends essentially on the density, anisotropy, and inhomogeneity of the dielectric. Thus, shape and structure of the specimen must be standardized. For on-the-go sensing the measurement of the heat capacity or heat conductivity is less suitable because of long response times. The accuracy and reproducibility of other electromagnetic contact methods like time domain reflectometry (measurement of the wave velocity) or microwave moisture sensing (attenuation of electromagnetic energy at wave guides, strip lines, cables, etc.) is not satisfactory for field measurements [36,37].

Out of the non-contact methods the Proton-NMR has the best potential, because the concentration of water molecules is measured directly and sensing of water profiles up to a depth of about 15 cm is possible. Mass and cost prevent NMR to be a practicable sensor. The evaluation of the soil surface colour (VIS reflectance) and temperature (IR thermometry) gives insufficient results. The best way could be a combination of X-band radar (3 cm wavelength) with an IR reflectance ratio meter [7] for water absorption (e.g., 1930 nm in relation to 1100 or 1300 nm), since IR gives information of surface moisture and with the X-band reflectance a more detailed information on the distribution of the moisture in the top soil could be gained.

### Principles and trends for sensing of dynamic soil properties

Physical and technological properties of the soil like compressibility, shear strength, friction, consistency, penetration resistance, etc. influence tillage and crop production directly. Usually the penetration resistance is determined at widely separated discrete positions of the field once or twice a year, if at all. The knowledge of the vertical and horizontal density distribution would be of advantage for site-specific agriculture, since tillage is often the most costly input for crop production.

Attempts have been made for more than three decades in development of equipment for on-the-go determination of soil mechanical impedance. A horizontally operating penetrometer with continuous analogue registration (Fig. 4) has been developed and tested in Bornim by Lindner and Zschaage [21,38] in 1962. This type of measurement has been improved by several authors [3,17,31]. A similar principle is the measurement of traction force of tillage-tools [11,25]. The force acting on a body moved in the soil may be written in terms of power of the speed as an approximation:

$$F = \mu_s A_s p_s + A_{\mathrm{rheo}} v + A_{\mathrm{dyn}} v^2 \quad (1)$$

The first term reflects the kinetic friction ($\mu_s$ - coefficient of friction, $A_s$ - effective surface of the body, $p_s$ - pressure on the body), in which $p_s$ is influenced by the local density. The second term $A_{\mathrm{rheo}}$ is determined by the rheological properties of the soil (viscosity, plasticity and elasticity) in relation to the rate of the volume displaced during motion of the body and does not depend on soil density directly. The third term $A_{\mathrm{dyn}}$ corresponds to the hydrodynamic resistance, usually applied to Newtonian fluids, but the direct proportionality to the density should be valid too, when soil is treated as non-Newtonian fluid. These considerations indicate the dependence of the measured force on the soil density and make visible the difficulties, since the force depends on the speed and on the depth of the moving body as well as on structural and compositional (or rheological) quantities.

Another interesting principle for soil density measurements is the infiltration of conductible liquids [18], which has the potential for automation. For the control of tillage, especially quality of seedbed structure (size distribution of soil aggregates in the surface of the seedbed) principally the technique of machine vision can be applied [6,32]. Although a system for fast sensing of well-defined physical and other traditional soil quantities does not exist, the possibility of using force measurements and computer vision for control of soil cultivation seems to be satisfying for the first needs in site-specific cropping.

## TRENDS IN PLANT SENSING: PROPERTIES, PRINCIPLES AND SENSORS

The spectral analysis of the colour of plants has a tradition of more than five decades. Optical methods are the way for remote sensing of plants, since detailed information can be got from spectral and spatial intensity distribution. Therefore, spectral machine vision is favoured in the research now. The additional advantage is that hard- and software solutions from the field of industrial research and development can be adapted to the agricultural engineering research tasks. Since image evaluation is not a cheap technology, simpler solutions are looked for.

The state of plants may be sensed by spatially low resolved spectral measurements [e.g., 4,9,16,24,29]. As an example for the wide scope of this research the paper of Amon *et al.* [4] may be quoted. They studied corn, barley and wheat in the range 400-2000 nm with a receiver at 10 m above the plants and an evaluation site of about 6 m$^2$. A clear influence of the soil and plant management on the ratio of reflectance IR/VIS (800 nm / 670 nm) has been found.

High resolving techniques are necessary for plant recognition or plant identification. The digital image processing has a short history of around two decades. Meanwhile, hundreds of papers were published dealing with imaging in agriculture and life science. Few examples are given in the references [2,13,15,20,26,35]. One way is the application of commercial video equipment with software for data reduction and evaluation. The other way is the search for optimal wavelengths at first, to get maximum contrast for the special plant or effect looked for, then an adequate optical equipment for taking images must be chosen, and, finally the search for

**Fig. 4.** The original horizontal penetrometer as used by Linder and Zschaage [21].

time- and cost-effective hard- and software follows. By these principles optical sensor systems have been developed. Broad and daily increasing experience is available now, but the cost and the power of commercial image processing systems do not correspond to agricultural requirements still.

## CONCLUSIONS

1. Sensors are needed in site-specific crop production for the control of those properties of soil and plants, which are spatially variable, essential for economy and environment, and, which cannot be recognized by the farmer during field-work immediately.

2. The sensing of soil nutrient content by ion-selective electrodes has the advantage of direct concentration measurements, but is connected with the disadvantage of the more complicated and less reliable contact principle. By means of spectral reflectance analysis in the red and near infrared range the organic matter content can be estimated. Further practical experience must be collected to show the usefulness of this development.

3. Although there are many principles and methods for soil moisture determination, no solution has become the standard in on-line monitoring at field-work. The combination of microwave and infrared radiation might have the best potential for remote soil moisture sensing.

4. Sensors and measuring principles for remote sensing of the density and other structural properties of the soil are not known except X-ray or gamma-ray scattering. High ionizing radiation is not practicable in agriculture. For the determination of local variations in soil density the traction force of special formed tillage tools or the pressure acting on a horizontally moved penetrometer may be used. Actual research on sensors for the evaluation of seedbed quality is based on machine vision mainly, since hard- and software principles known from other developments are transformable to agricultural engineering tasks.

5. Sensors for plant recognition and plant evaluation are based upon spectral evaluation in the VIS and NIR range and image processing. Machine vision is expensive still, therefore, multispectral methods with low spatial resolution could be cost-effective alternatives in the development of sensors for the evaluation of crops.

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